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# OPTIMAL POSITIONING THE VALVES OF THE MULTIPLE STEAM NOZZLE CONTROL SYSTEM OF STEAM TURBINE

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**Abstract.** *In this paper the model of computation of steam nozzle control systems with the given consumption of a working medium is considered, in which the task of shut-off elements positioning of control valves has been solved with the support of combinatorial algorithms. Thus the loading between the nozzle control systems segments of adjusting stage distributes in such a manner that the maximum possible power capacity of an adjusting stage is reached for each given steam consumption. The model describing joint operation of steam nozzle control system, the adjusting stage and the flow path of multicylinder steam turbine has been reviewed and analyzed.*

## Nomenclature.

### Symbols

$G_s$ – the calculated value of a mass flow of steam through the adjustment stage;
$G_g$ – the designated value of a mass flow of steam through the adjustment stage;
$H_v$ - lifting height of the shut-off element of the control valve;
$H_v$ -lifting height of the shut-off element of the control valve;
$H_v^{max}$ - maximum lifting height of the shut-off element of the control valve;
$F_m$ – an array of summary squares nonrecurring combinations of nozzle segments of adjusting stage;
$EFF$ -coefficient of efficiency;
$N$ - power capacity of the turbine unit;
$N_{as}$ – power capacity of the adjusting stage;
$\eta_t$ – thermal efficiency of the cycle;
$\eta_{oi}$ – internal relative efficiency of the turbine flow path;
$\eta_a$ – absolute efficiency of the cycle;
$Q_t$ – heat supplied in the cycle by burning fuel;
$n$ – control valve number;
$H_o$ - heat drop of the adjusting stage.

### Abbreviations

HPC – high pressure cylinder;
IPC – intermediate pressure cylinder;
LPC – low pressure cylinder;
SNCS -multiple steam nozzle control system.

## INTRODUCTION

Issues related to the projection of optimal flow path designs of powerful steam turbines are the subject of a lot of work. Among that work, the most important and relevant today are the papers devoted to the problems of obtaining solutions capable provide researches with the highly effective work of axial turbines in the vast variety of operational modes [1, 2]. Of course, it is impossible to adequately take into consideration the impact of mode parameters on the effectiveness of axial turbines performance without the use of calculation models of steam control systems. In most designs the powerful steam turbine management of operational modes is carried out by means of multiple steam nozzle control systems (SNCS).

In this regard, issues related to modeling work are important. Of particular relevance were those obtained due to the principal capability of modern control systems which provide an independent positioning of control valves [3]. The application of such management systems allows the transferring to a new class of optimum design problems, the solution of which will ensure the mutual influence of the parameters of the SNCS and the rest of the flow path on the axial turbine efficiency.

## THE PURPOSE OF THE STUDY

The optimal design of SNCS includes, among other factors to be improved, the geometrical parameters of control valves play a vital role. These include the shut-off element positioning options.

The aim of this study is to develop effective combinatorial algorithm for finding such a combination of shut-off elements positions of the control valves of the SNCS, which guarantees that the adjusting stage operates with maximum output for any given steam consumption.

The model describing joint operation of steam nozzle control system and the flow path of multicylinder steam turbine has been reviewed and analyzed.

## MAIN CONTENT

The solution of the assigned task is carried out using a model in which positions of the valves shut-off elements are defined by application of appropriate optimization algorithms to ensure the passage of specified steam consumption. [4]. Optimal design of SNCS combined with the axial turbine flow path requires reiterative use of these algorithms and expenditure of significant time resources.

The proposed model and algorithms of calculation of the SNCS provide the required positioning the valves shut-off elements using a more rational approach. One based on the application of a combinatorial optimization algorithm that takes into account the physical features of the SNCS functioning.

In this case, the combination of positions of the valve shut-off elements provides the operation of the adjusting stage that is close to the maximum possible produced power capacity for any given steam consumption (i.e., we have a complete analogy with the model based on a solution of the optimization problem with the quality criterion – the power capacity of adjusting stage) [4], that is more efficient in terms of the time expenditure required for this task.

The most important part of the developed model is the combinatorial algorithm. This allows determination of the required capacity for operation the combination of nozzle segments at the adjusting stage, as well as the value of lifting the valves shut-off elements.

It is known that at intermediate operating modes the power capacity of adjusting stages are mainly determined by the steam consumption and the size of its disposable thermal drop. The change in the efficiency of the adjusting stage in these cases is less important. In turn, the amount of disposable thermal drop at the adjusting stage is determined by the disposable thermal drop of the nozzle segments.

The size of the latter significantly depends on the throttling degree of steam on the control valves, which allow the steam to pass through a nozzle segment. The smaller the level of throttle, the bigger the role of the thermal drop that will be wrought on the appropriate segment of the adjusting stage.

For a given steam consumption the minimum level of throttle of working medium on control valves is carried out at the maximum opening of the shut-off element connected with the minimum required space of the working nozzle segments.

Therefore, the problem of defining nozzle segments combination, which provides the given steam consumption with a minimal degree of throttle on the relevant control valves, is essentially equivalent to task of finding the combination of nozzle segments with the minimum necessary total area to pass the required steam consumption.

By determining the combination of segments for each particular amount of mass flow, we will automatically arrive at a solution that provides the highest level of disposable heat drop of the adjusting stage, and, therefore, the maximum value of its capacity.

In view of the above, the considered problem can be formulated as follows: among the various combinations of segments, which jointly allow the passage of the required steam consumption, it is necessary to find the combination that has the smallest total area.

Thus, the solution to the problem is based on minimizing losses from throttling the steam by maximizing the upswings shut-off elements of control valves thereby allowing operation of the adjusting stage with the maximum possible thermal drop.

For its solution the combinatorial algorithm of formation of the summary areas array of various combinations of adjusting stage segments is used. For example, for adjusting stage with four segments the following combinations of segments will be included in the corresponding array $F_m$ (Fig. 1):

- The area of individual segments with the numbers 1, 2, 3, and 4.
- The total area of the paired combinations of segments with the numbers 1-2, 1-3, 1-4, 2-3, 2-4, 3-4.
- The total area of combinations on three segments, respectively, 1-2-3, 1-2-4, 1-3-4, 2-3-4.
- The total area of all the segments 1-2-3-4.

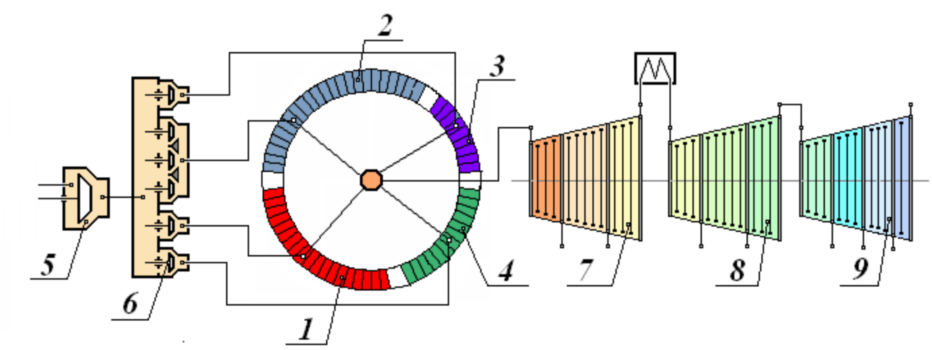


Fig.1. 1-4 - number of segment of the adjusting stage, 5- stop valve, 6- shut-off element, 7 – HPC, 8 – IPC, 9 – Low Pressure Cylinder (LPC).

Sorting the array elements $F_m$ in ascending order we will get the ordered sequence of twelve unique combinations of segments and their associated control valves. Estimation of output capacity of considered combinations of operating segments is done using a model of joint computation of steam nozzle control and turbine flow path [4].

Block diagram of the computation algorithm of combinatorial problem is given in Fig.2.

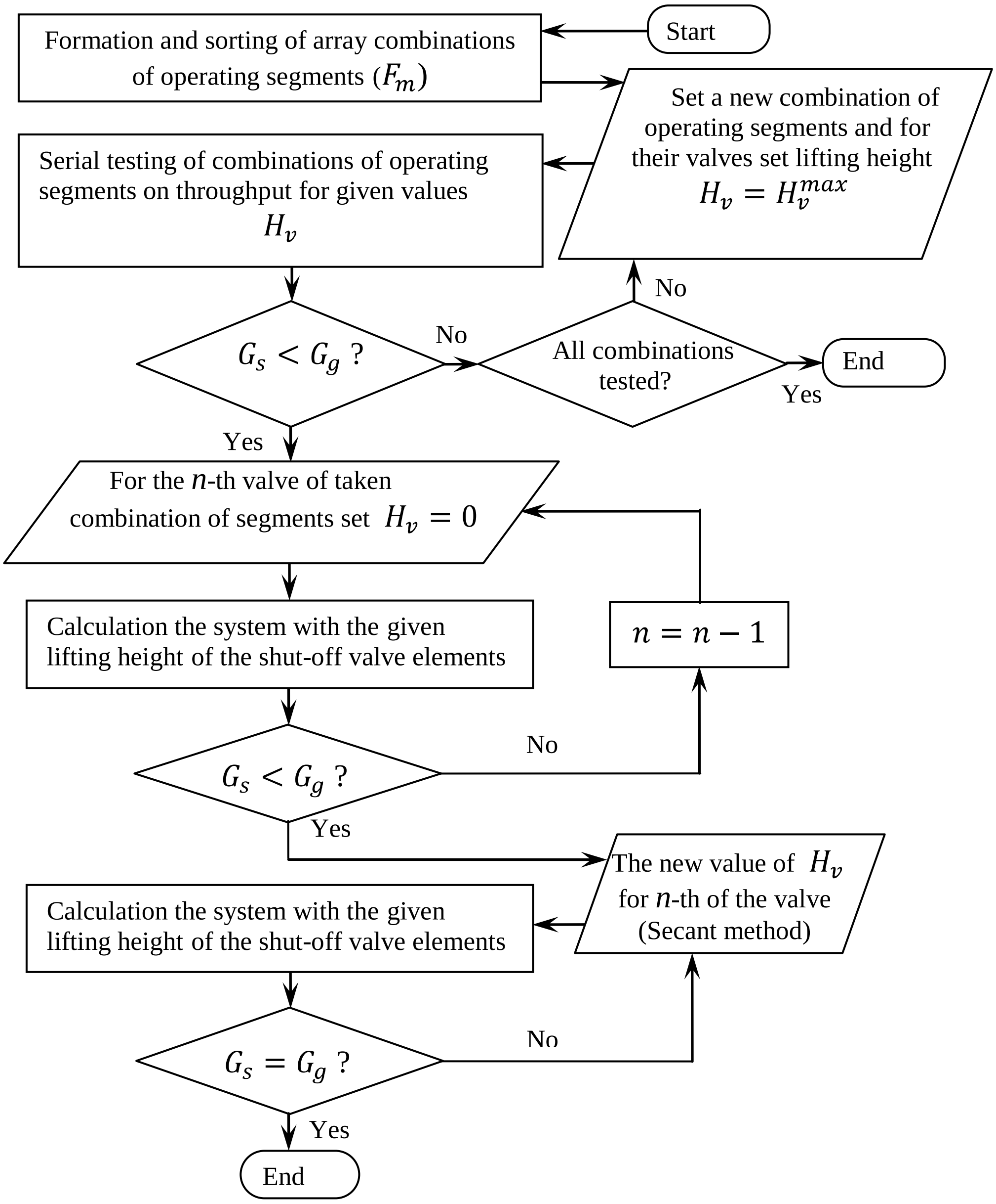


Fig. 2. Block diagram of the algorithm for searching the required combination of operating segments and determine the position of the active control valves for given steam consumption

As you can see from Fig.2, in the first phase of the algorithm the necessary combination of operating segments with simultaneous verification of the throughput of the system is followed.

To do this for each inspecting combination of segments, the full opening of all related control valves is simulated and computation of all systems of the model with the given value of lifting for the shut-off elements of the control valves are taken [4]. If the result of the calculation is that $G_s < G_g$ the algorithm selects another combination of operating segments that has more total area, and the operation described above is repeated.

In the event that all the segments of the adjusting stage are involved and it turns out that eth $G_s < G_g$ algorithm has completed its work. With the steam consumption equal to the maximum pass ability of the design of turbine nozzle, steam control will be determined.

After the required combination of operating segments is defined, the algorithm will find the control valve (from the number of active valves for a given combination of nozzle segments) in the operation area in which the specified flow rate is available. For finding such a valve two conditions are required: $G_s > G_g$ – at fully open the valve and $G_s < G_g$ – at fully closed valve. The exact value of lifting for each valve, ensuring passage of the required steam flow, is determined by the numerical solution of the equation $G_s = G_g = f(H_v)$.

The secant method is used for solving this equation.

It should be noted that with the steam consumption not very different from the nominal value, the proposed model is similar to traditional solutions, which are characterized by a consecutive opening and closing of the segment valves.

At the same time, at the lower modes of turbine operation derived solutions differ significantly from traditional, as the different nozzle segments of adjustment stage are switched into operation. With this a higher power capacity of the adjusting stage and the entire turbine as a whole is achieved .

As an example, Table 1 shows the lifting height of the shut-off elements of control valves obtained through traditional and combinatorial modeling of its position for different steam consumptions.

Table 1.

Lifting height shut-off elements of control valves of multiple steam nozzle control system the turbine K-310-240 when modeling traditional and combinatorial positioning

| $G_g$, kg/s | The traditional positioning of the shut-off elements of control valves | | | | | | The combinatorial positioning of the shut-off elements of control valves | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Segment №1 | | | | Segm №2 | Segm №3 | Segment №1 | | | | Segm №2 | Segm №3 |
| | $H_{v1}$, *mm* | $H_{v2}$, *mm* | $H_{v3}$, *mm* | $H_{v4}$, *mm* | $H_{v1}$, *mm* | $H_{v1}$, *mm* | $H_{v1}$, *mm* | $H_{v2}$, *mm* | $H_{v3}$, *mm* | $H_{v4}$, *mm* | $H_{v1}$, *mm* | $H_{v1}$, *mm* |
| 50 | 5,11 | 5,11 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 6,42 | 0,0 |
| 70 | 7,30 | 7,30 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 9,34 | 0,0 |
| 110 | 11,23 | 11,23 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 15,31 | 0,0 |
| 150 | 15,32 | 15,32 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 21,85 | 4,82 |
| 230 | 27,01 | 27,01 | 29,23 | 29,23 | 4,32 | 0,0 | 27,01 | 27,01 | 29,23 | 29,23 | 0,0 | 4,22 |
| 270 | 27,01 | 27,01 | 29,23 | 29,23 | 21,85 | 2,76 | 27,01 | 27,01 | 29,23 | 29,23 | 21,85 | 2,76 |
| 277,8 | 27,01 | 27,01 | 29,23 | 29,23 | 21,85 | 7,49 | 27,01 | 27,01 | 29,23 | 29,23 | 21,85 | 7,49 |

All the calculations were carried out with invariable stagnation parameters of pressure and enthalpy before the control valve and at a constant value of static pressure beyond the last stage of the low pressure cylinder.

Fig. 3-8 shows the differences between the main characteristics of turbine and its adjustment stage in traditional modeling positioning control valves and their positioning determined with the assistance of finding of the combinatorial tasks under consideration.

The numbering of the curves in the figure corresponds to the rules of modeling lifting of shut-off elements of control valves: 1- combinatorial positioning, 2 - traditional positioning.

As can be seen from Fig. 3 and Fig. 4, application of a combinatorial algorithm for determination the combinations of operating segments and the appropriate positioning of control valves linked with its control segments, improves the efficiency of the turbine and gains a significant increase in turbine capacity, particularly in modes of operation other than the nominal.

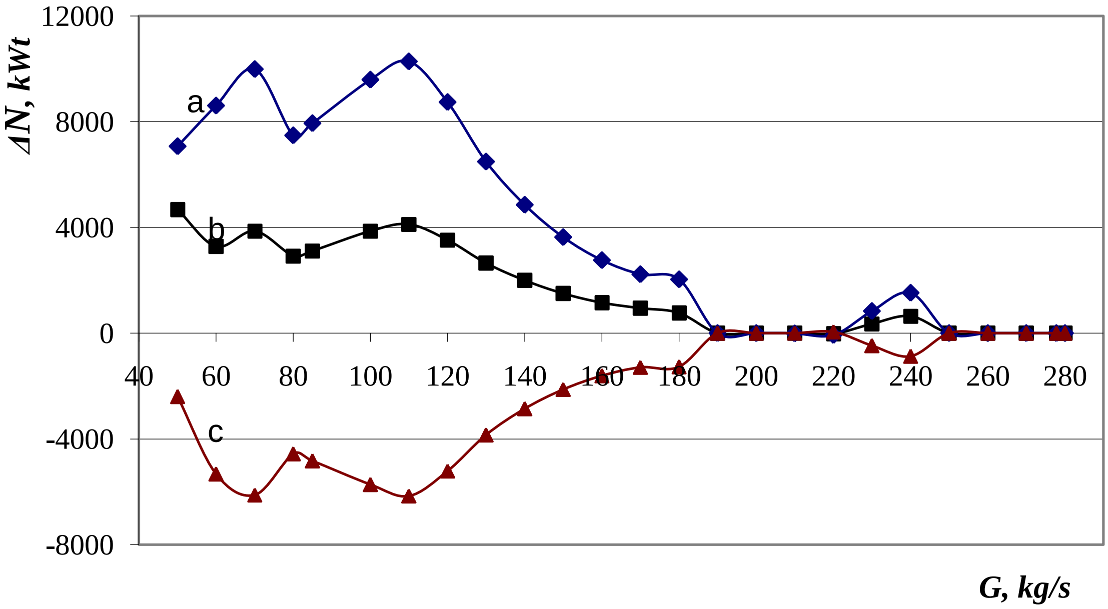


Fig. 3. The power changes of the turbine K-310-240 and separate its parts
a)-adjusting stage; b)- power increase in the turbine as a whole, resulting from the use of combinatorial algorithm c) the sum of the power of HPC (without adjusting stage), IPC and Low-Pressure Cylinder;

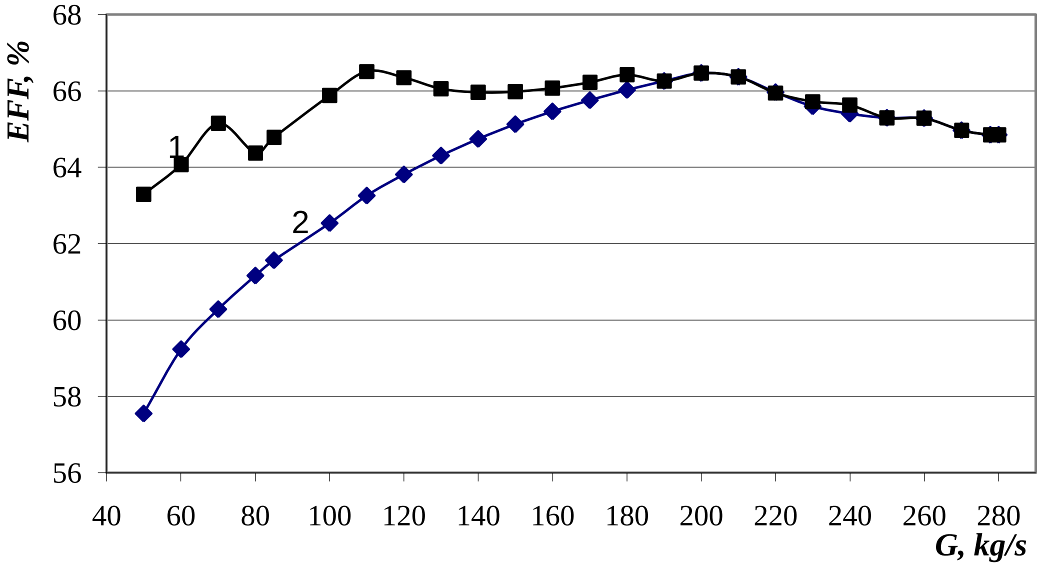


Fig. 4. Efficiency of the turbine K-310-240 at different steam consumption
1 – combinatorial positioning, 2 - traditional positioning

The obtained results are explained quite well by Fig. 5-8.

In Fig. 5 you can see that the efficiency of the adjusting stage with traditional positioning of the shut-off elements of the control valves in most parts of the consumption steam range exceeds the efficiency obtained when using the above combinatorial algorithm for operating segments and positioning of related control valves.

However, due to the fact that the combinatorial algorithm allows finding combinations of the operating segments with a minimum total throughput capacity of an area, it is possible to significantly increase the disposable heat drop of the adjusting stage (Fig. 6) and, consequently, increase its power capacity (Fig. 7) in most parts of the consumption steam range.

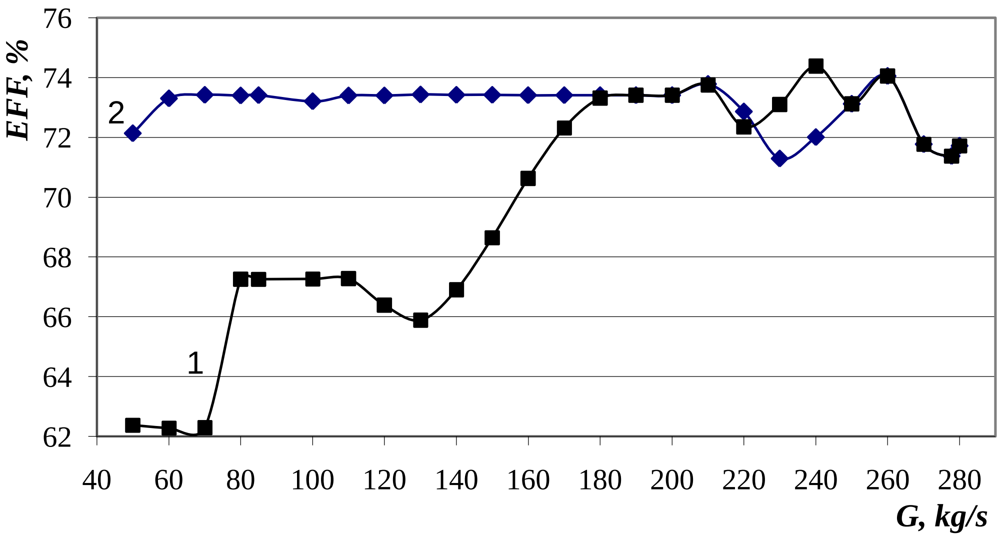


Fig. 5. Efficiency of the adjusting stage of the turbine K-310-240 1 at different steam consumption
1 – combinatorial positioning,    2 - traditional positioning.

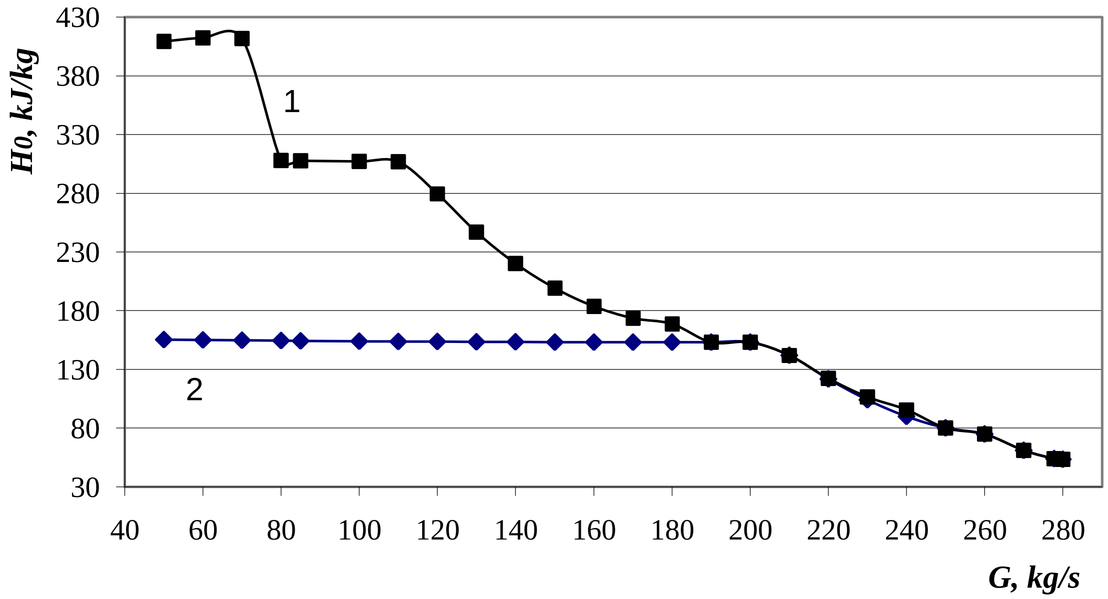


Fig. 6. The disposable heat drop of the adjusting stage of the turbine K-310-240 1 at different steam consumption 1 – combinatorial positioning, 2 - traditional positioning.

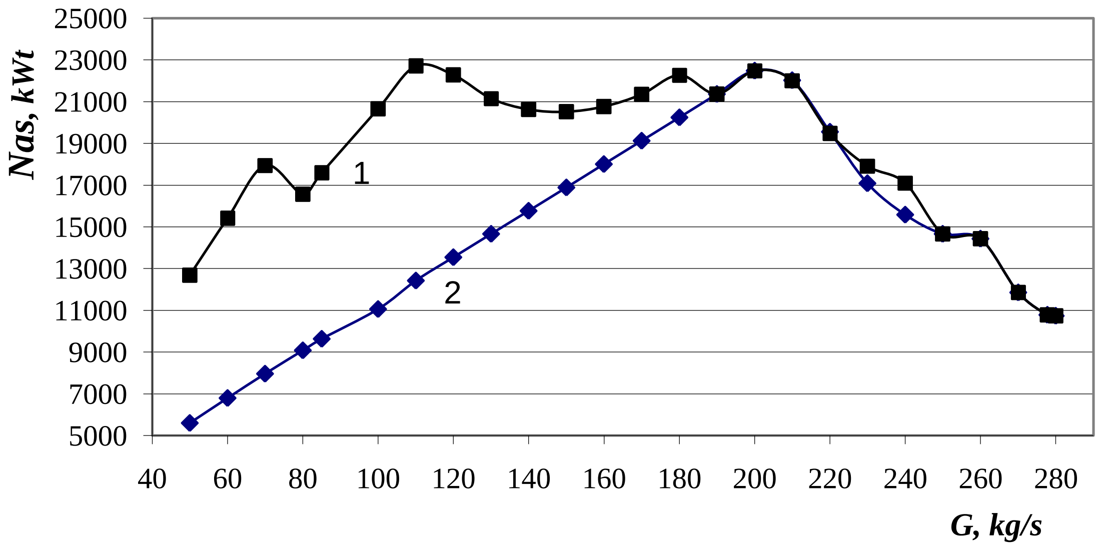


Fig. 7. The power capacity of the adjusting stage of the turbine K-310-240 1 at different steam consumption 1 – combinatorial positioning, 2 - traditional positioning.

A significant increase in the power capacity of the adjusting stage has a positive effect on the power of the whole turbine and its efficiency (Fig. 3, 4).

In addition, the comparative analysis of the expansion process of steam (Fig. 8) and steam cycles shows that the use of the proposed combinatorial algorithms for manipulation of control valves allows not only for an increase in the power capacity of the turbines at reduced modes of operation, but also increases the overall efficiency of the cycle (Table 2.).

Table 2.
The efficiency of cycles of the steam turbine K-310-240 at the mass flow consumption of steam 70 kg/s

| Variant | $\eta_t$, % | $\eta_{oi}$, % | $\eta_a$, % | $N$ *kW* | $Q_t$, *kJ /kg* |
|---|---|---|---|---|---|
| 1- Combinat. | 45,799 | 81,252 | 37,213 | 80803.7 | 2987,80 |
| 2- Traditional | 41,848 | 86,269 | 36,102 | 76936.0 | 2889,63 |
| Difference | 3,95 | -5,02 | 1,11 | 3867.7 | 98,17 |

Results of comparative computations of considering steam cycles, presented in Table 2, shows, on the one hand, that the use of combinatorial algorithm for guiding the control valves increases the thermal efficiency of the cycle ($\eta_t$), but on the other hand, leads to a reduction of internal relative efficiency of the turbine flow path ($\eta_{oi}$).

The latter is connected with the deviation of steam parameters from calculated values when mode of flow is changing (especially in HPC), which in turn leads to an increase in supply to a working medium in the boiler of needed heat $Q_t$. However, the substantial increase of the disposable heat drop of the adjusting stage (Fig. 8) and, consequent increase in the power capacity of the turbine unit ($N$) provides an overall positive result and increases the absolute efficiency of the cycle ($\eta_a$) of 1.11%. Thereby reducing the specific consumption of equivalent fuel to produce 1 *kW* at the same value.

The calculations have shown that the use of combinatorial positioning shut-off elements of control valves in combination with the modern systems of control of their positions (with the ability to provide individual independent positioning of each valve), will allow better use of reserves by increasing the efficiency of multiple steam nozzle control systems and the turbine as a whole.

The obtained results also highlight the importance and the need to address the problem of optimal design of turbine multiple steam nozzle control system, taking into consideration the schedules of potential modes of operation of the turbine unit.

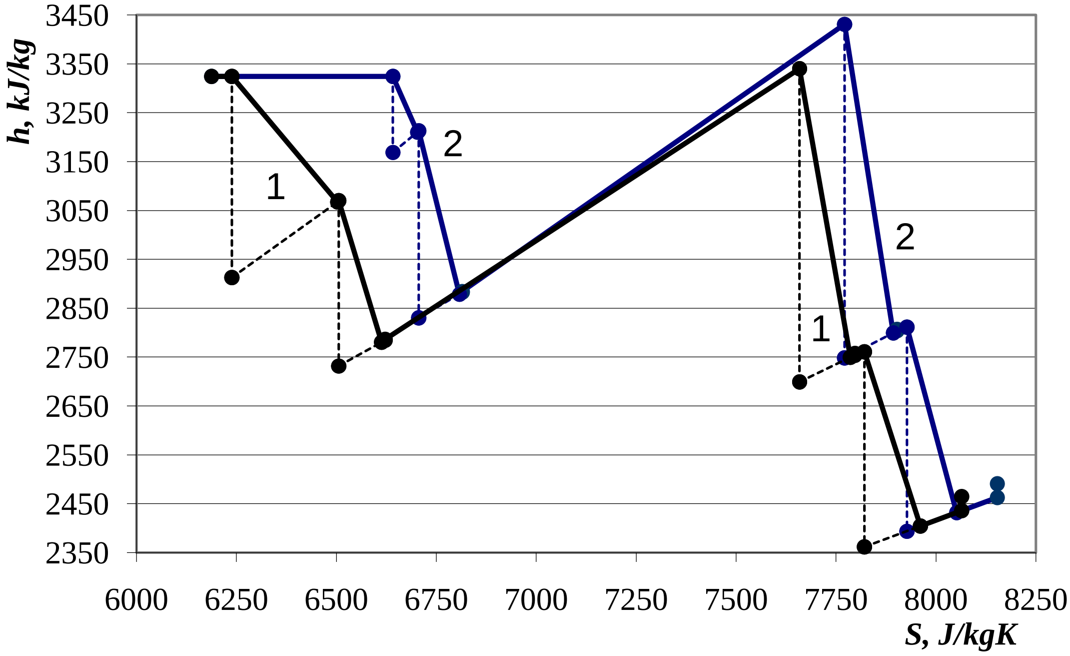


Fig. 8. Enthalpy- Entropy diagram of expanding steam processes in the turbine K-310-240 at the mass consumption of steam 70 kg/s

It should be noted that the results of optimization based on simulation of the impact on the efficiency of the turbine and the steam cycle of the shut-off elements positions of control valves, can find its application in the software and hardware of complex electro-hydraulic control systems [3] in the form of information on optimal valve positions for any combination of operating parameters. These parameters, in this case, include the consumption of steam, pressure in the condenser, the value of steam takeoff on regenerative heating etc.

Within the scope of this work issues related to assessing the strength of the elements of the adjusting stage were not addressed, neither were issues related to changes in absolute magnitude and direction of the vector of the force acting on the rotor. They certainly should be addressed in a real design of HPC and multiple steam nozzle control system of turbine.

## CONCLUSIONS

- A combinatorial algorithm for controlling of shut-off elements positioning of control valves was worked out and a new problem statement of computation of steam nozzle control system to ensure the minimum throttling losses was implemented.
- The carried out computation analysis have confirmed the appropriateness of the use of combinatorial algorithm in optimal design of steam nozzle control system together with optimization of steam turbine flow path, taking into account their operatinal mode.
- A significant impact of shut-off elements positioning of control valves on the efficiency of the turbine and steam cycle as a whole confirms the need for a design of system of individual governing of nozzle steam distribution valves.

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